

Electron cloud driven vacuum instability

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Abstract. Electron clouds are shown to cause pressure rises in the Relativistic Heavy Ion Collider. In a number of cases beam induced vacuum instabilities were seen where the pressure grows exponentially with time. We analyze under which conditions electron clouds can lead to these vacuum instabilities. We consider as the feedback mechanism for the instability the following: rest gas ionization by electrons in the cloud and the beam, subsequent acceleration of the ions by the beam, and molecular desorption induced by the ions hitting the wall, leading to increased pressure and thus higher ionization rates.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) consists of two superconducting rings, named Blue and Yellow. Since 2001 vacuum pressure rises were observed with intense ion beams. While this could be seen initially only at injection, later observations were also made at store and at transition. Pressure rises were observed with all species (Au^{79+} , d^+ , p^+), and with two exceptions, only in the warm interaction regions. A summary of the observations, and further references can be found in [1].

A number of effects were considered to account for the observed pressure rises [2]. The existence of electron clouds in conjunction with pressure rises could be confirmed by observing the tune shift in bunch trains [3], and by direct observation with electron detectors [4]. The ionization of rest gas by the beam, subsequent acceleration of the ions in the beam field, and the desorption when the ions hit the wall, is only a possibility for ions with high charge states. The contributions of beam losses are still under investigation, and anti-grazing rings were proposed for mitigation [5].

In a number of cases pressures growing exponentially with time were observed (see Fig. 1 for an example). Here we analyze under which conditions electron clouds can lead to these vacuum instabilities.

OBSERVATIONS

Fig. 1 shows an example of a pressure rise instability in the Blue ring that limited the beam intensity during the 2004 operating period. The pressure rise occurred in the collimator region that was not baked due to scheduling conflicts. The Yellow collimators were baked, and no vacuum instabilities were observed there.

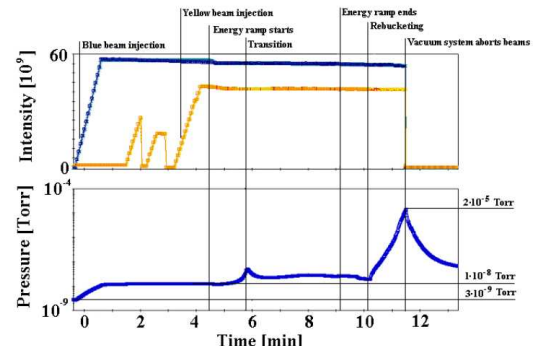


FIGURE 1. A vacuum instability with Au beam in the Blue ring. The upper part shows the total intensity for both rings during injection, acceleration, and storage. The lower part shows the pressure in the Blue collimator region, with an exponential increase after rebucketing.

The Blue ring is filled first, resulting in a slight pressure increase. After the Yellow beam is filled both beams are accelerated. A pressure increase is visible when transition is crossed, as the bunches get shorter. The pressure drops back after the transition crossing. When the bunches reach the flattop energy, they are transferred from the accelerating rf system with harmonic number 360 into the storage rf system with harmonic number 2520. In the process, the bunch length is reduced by about 50%. After rebucketing, the pressure increases exponentially with a time constant of 11.7 seconds until the vacuum interlock system aborts the beams. It is likely that the bunch shortening triggered the formation of an electron cloud. This has also been seen at another location in the ring [6]. No electron detectors are installed in the collimator region. The beam parameters are listed in Tab. 1. A second pressure instability of the same type was observed with 61 bunches of $0.9 \cdot 10^9$ average intensity, with a growth time of 5.9 seconds. For operation the beam intensity was kept below the instability threshold.

To clarify the role of electron clouds and beam loss 2 tests were made. First, Au bunches were injected with different spacings. Second, a local beam loss was created

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² At the workshop the author presented the overview talk “Electron clouds and vacuum pressure rise in RHIC”. Most of the material in the talk is documented in Ref. [1]. Here an more detailed analysis of a particular aspect is presented that was not published previously.

TABLE 1. Input parameters, computed critical desorption coefficients η_{crit} for H_2 and CO , and measured and computed pressure growth times for the unbaked Blue collimator region. The parameters for gold correspond to the vacuum instability shown in Fig. 1. The value for protons show the highest injected proton intensity, for which no instability developed.

parameter	unit	Au ⁷⁹⁺	p ⁺
<i>beam parameters</i>			
charge, mass number Z, A	...	79, 197	1, 1
relativistic γ	...	107.4	25.9
particles per bunch N_a	10^9	1	170
no of bunches N_b	...	56	111
revolution freq. f_{rev}	Hz	$7.8 \cdot 10^4$	
<i>vacuum system</i>			
pressure P_0	Torr	$1.0 \cdot 10^{-8}$	
temperature T	K	300	
pipe radius r	m	0.08	
conductance c_{H_2}	$m^4 s^{-1}$	0.56	
conductance c_{CO}	$m^4 s^{-1}$	0.15	
space betw. pumps $2L$	m	11.4	
<i>ionization by cloud electron [3, 4, 6, 7]</i>			
current into wall dI_e/dl	A/m	0.03	
average electron energy	eV	50	
cross section σ_{e,H_2}	m^2	$9.8 \cdot 10^{-21}$	
cross section $\sigma_{e,CO}$	m^2	$2.2 \cdot 10^{-20}$	
<i>ionization by beam [8, 10]</i>			
cross section σ_{b,H_2}	m^2	$1.3 \cdot 10^{-19}$	$2.2 \cdot 10^{-23}$
cross section $\sigma_{b,CO}$	m^2	$5.8 \cdot 10^{-19}$	$1.0 \cdot 10^{-22}$
ion energy at wall	eV	15	62
reported η_{H_2} [8]	...	0.4	1.5
reported η_{CO} [8]	...	0.3	1.2
desorp. coeff. η_{crit,H_2}	...	42	131
desorp. coeff. $\eta_{crit,CO}$...	2.8	14
growth time meas. τ	s	6-12	
growth time calc. τ_{H_2}	s	23.4	
growth time calc. τ_{CO}	s	5.4	

by moving in one of the Blue collimators. In the first test 53 bunches with 108 ns spacing and 10^9 bunch intensity lead to a pressure of $7 \cdot 10^{-6}$ Torr. Injection of approximately the same amount of beam with twice the bunch spacing lead to a pressure of only $4 \cdot 10^{-8}$ Torr. In the second test a local beam loss of $7 \cdot 10^7$ Au ions within 5 second did not induce any pressure rise. Thus the pressure rise in the collimator region is sensitive to bunch length and bunch spacing, but not to local beam losses. This is consistent with electron clouds as the mechanism driving the pressure rise.

Before 2004, exponential pressure rises were also seen at injection, with growth times ranging from 1.7 to 7.1 second. In all these cases Au beam was injected, and the pressure rise occurred in unbaked regions.

ANALYSIS

To describe the pressure evolution P we consider a model that includes a static gas load Q_0 , a load Q_1 from elec-

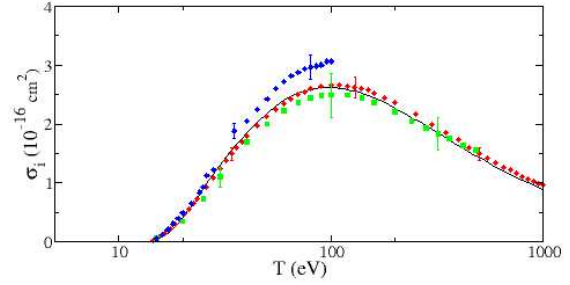


FIGURE 2. Ionization cross section of CO molecules as a function of the electron impact energy [7]. The solid line shows the output of a model, the colored points denote 3 different measurements.

trons in a cloud hitting the walls, a load Q_2 from rest gas molecules ionized by the cloud electrons and accelerated by the beam, and a load Q_3 from rest gas molecules ionized and accelerated by the beam. The total load is then

$$Q = Q_0 + Q_1 + Q_2 + Q_3. \quad (1)$$

We will derive a criterion for vacuum stability, and estimate the growth time in an unstable situation. We compare expectations from the model with observations.

We model the collimator region as a periodic structure with pumps of pumping speed $2S$ spaced by the distance $2L$. The three pumps in the region are spaced by 9.2 m and 11.4 m, and the conductance c varies due to the insertion of the collimators. We take limiting values for $2L$ and c (see Tab. 1) for the calculations.

Stability criterion

We consider the equilibrium $Q = SP$. The load Q_1 per length L is

$$Q_1 = kT \frac{L}{e} \frac{dI_e}{dl} \eta_e \quad (2)$$

where k is the Boltzmann constant, T the absolute temperature, e the elementary charge, and dI_e/dl the electron current into the wall per unit length. η_e is the average desorption coefficient for the energy distribution of the cloud electrons. A pressure change will affect the rate at which rest gas molecules are ionized and electrons generated. However, in simulations the variation of the electron generation rate did not change the electron cloud density nor the time to reach saturation [3]. We therefore assume that the gas load Q_1 does not depend on the pressure P , and thus will not lead to an instability.

The load Q_2 can be estimated as

$$Q_2 = \sigma_e P \frac{2rL}{e} \frac{dI_e}{dl} \eta_{ion} \quad (3)$$

where σ_e is the cross section for rest gas ionization from an impact of cloud electrons, r the beam pipe radius, and η_{ion} is the average desorption coefficient for ions accelerated by the beam. Values for σ_e can be found in [7], an example for CO is shown in Fig. 2. The gas load Q_3 is [8]

$$Q_3 = \sigma_b PL N_b \eta_{ion} \quad (4)$$

where σ_b is the cross section for the rest gas ionization, \dot{N}_b is the beam particle flow, i.e. the number of particles in the beam divided by the revolution time. In equilibrium we have $PS = Q$, where S is the pumping speed. Introducing the parameter

$$b = \sigma_e \frac{2r}{e} \frac{dI_e}{dl} + \sigma_b \dot{N} \quad (5)$$

we therefore get for the equilibrium pressure measured at the pump

$$P = \frac{Q_0 + kT \frac{L}{e} \frac{dI_e}{dl} \eta_e}{S - \eta_{ion} L b} \quad (6)$$

From Eq. (6) a stability condition can be derived. However, in conductance limited systems a more stringent condition applies and the maximum desorption coefficient becomes [8]

$$\eta_{crit,ion} = \frac{\pi^2}{4} \frac{c}{bL^2}. \quad (7)$$

Pressure growth time

The pressure follows the differential equation [9]

$$v(x) \frac{\partial P(x,t)}{\partial t} = a(x) + b(x)P(x,t) + c(x) \frac{\partial^2 P(x,t)}{\partial x^2} \quad (8)$$

where $v(x)$ is the volume per unit length, $a(x)$ the static gas desorption per unit length, and $b(x)$ and $c(x)$ were introduced above. In a situation with exponential pressure rise the static load $a(x)$ can be neglected, and we make the ansatz

$$P(x,t) = e^{t/\tau} p(x). \quad (9)$$

where τ is the growth time. Introducing the variable

$$\omega^2(x) = \frac{b(x) - v(x)/\tau}{c(x)} \quad (10)$$

Eq. (8) can be written as

$$\frac{d^2 p(x)}{dx^2} + \omega^2(x) p(x) = 0 \quad (11)$$

with the general solution $p(x) = Ae^{-i\omega x + \phi}$. From the symmetry condition $dp(x)/dx = 0$ at $x = L$ it follows $\omega(L) = 0$, or

$$\tau = \frac{v(L)}{b(L)} = \frac{\pi r^2}{b} \quad (12)$$

where r is the pipe radius, and b defined in Eq. (5). In our model this solution is equivalent to $\omega \equiv 0$ and ignores the pumping S . It will therefore underestimate τ but should give a useful approximation.

DISCUSSION

All input parameters are shown in Tab. 1 as well as the calculated critical desorption coefficients and growth times. Calculations were done for H_2 and CO while cross terms are neglected.

To get an estimate for actual desorption coefficients, we compute the energy E_{ion} of an ion with a single electron charge moving in the beam potential to the wall [11]:

$$E_{ion} = \frac{Ze^2 N_a}{2\pi \epsilon_0 L_{sep}} \ln \left(\frac{r}{\sigma_r} \right) \quad (13)$$

where σ_r is the rms beam radius, and L_{sep} the bunch separation. The reported desorption coefficients are still below the critical ones by about an order of magnitude, even when considering that Eq. (7) probably overestimates $\eta_{crit,ion}$ by some 30% [8]. We can only speculate that the actual ion desorption coefficients are larger than those reported in [8] or that there is a significant effect from ionization to higher charge states. In [8] only an interpolation is given between zero and 500 eV, and no measurements exist below 100 eV [12]. However, it is unlikely that desorption coefficients η_{ion} of 2 or more are reached for the beam currents in our case. The growth time calculated with the simple formula (12) is close to the measured growth time.

Significant uncertainty is also in the properties of the electron cloud. With our parameters, the ionization from the cloud electrons is about 20% of the beam ionization for Au ions. For protons the rest gas ionization can be neglected. This explains why no vacuum instability has been observed with protons. We also note that a vacuum instability based on beam losses would require the liberation of more than 10^9 molecules per lost ion.

Baking reduces the ion desorption coefficients by up to an order of magnitude [8], and at the same time the secondary electron yield. It should therefore suppress any vacuum instabilities. This is consistent with our observations. No vacuum instabilities were observed in baked areas. While vacuum instabilities can be suppressed, it is still possible to create intolerable pressure rises.

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